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Considerations on the shear strength behavior of weathered rockfill

Considérations sur le comportement de résistance de enrochement alteré

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ABSTRACT
A comprehensive investigation on the mechanical behavior of rockfill has been carried out in large-size shear devices in the laboratory. Triaxial and direct shear tests were performed on basalt riprap specimens from Marimbondo Dam in Brazil, which was constructed in 1975. The main results and conclusions on the shear strength envelopes are presented in this paper. Weathered riprap particles were collected at the region of water level fluctuation, where natural alteration by disintegration and decomposition of the basalt rockfill was noted to be more intense. An artificially weathered rockfill material was produced in the laboratory by continuous lixiviation in large Soxhlet equipment. Lixiviated basalt rockfill exhibits marked changes of surface chemical concentration, number of joints and deformability of rock particles. Processes of basalt weathering in the field and in the laboratory are compared in the paper. The methodology for accelerated weathering in the laboratory proved to adequately simulate the effects of field weathering, making possible a prediction of the long-term mechanical behavior of basalt rockfill. A significant reduction of the shear strength of weathered rockfill may be noted when compared to the intact material. The upstream rip-rap at Marimbondo Dam is predicted to remain competent as a slope protection material for at least more 50 years.

RÉSUMÉ
Une recherche sur le comportement mécanique des enrochements de barrage a été exécutée en utilisant des equipements de cisaillement à grande échelle dans le laboratoire. Les essais triaxiaux et de cisaillement directes ont été exécutées sur les échantillons de l'enrochement en basalte du Barrage de Marimbondo au Brésil, construite en 1975. Les principaux résultats et conclusions sur les enveloppes de résistance sont présentées dans ce travail. Les échantillons de l'enrochement alteré ont été rassemblées à la région de variation de niveau d'eau, où la alteration naturelle par désintégration et décomposition de l'enrochement en basalte a été notée plus intense. Des échantillons de l'enrochement artificiellement alteré ont été produites dans le laboratoire par lixiviation continue en appareil Soxhlet de grandes dimensions. Les particules d'enrochement en basalte lixiviées ont montré une alteration chimique accéntuée et de nombreuses fissures à la surface, ainsi que une deformabilité élevée. Les processus de alteration de basalte in situ et dans le laboratoire sont comparés. La méthodologie d'alteration accélérée dans le laboratoire est capable de simuler les effets de l'alteration in situ et de fournir une prédiction du comportement mécanique à long terme de l'enrochement en basalte. Il est noté une réduction considérable de la résistance au cisaillement de l'enrochement alteré par rapport à la roche intacte. L'enrochement de protection de la Barrage de Marimbondo est prédit compétent pour une période superiéure a 50 années.

1 INTRODUCTION

Rockfills are construction materials made of coarse particles, with average diameter ranging from milimeters to a few meters, in some cases. As a consequence, conventional laboratory equipment is not adequate for testing rockfills. Progress in understanding the behaviour of these coarse materials has been achieved mainly by monitoring the displacements of rockfill dams during and after construction in the field.

Large size devices in the laboratory have also been developed for investigating the shear behaviour of rockfills under controlled conditions.

However, there are still practical limitations for carrying out tests on actual rockfill materials in the laboratory (Maia, 2001). Geotechnical parameters obtained from small size rockfill specimens may not represent field behaviour (Marsal, 1977). Moreover, results from a field instrumentation program may be not adequate for other projects, unless similarity of rock materials and construction procedures are ensured.

Several factors may affect the mechanical behaviour of rockfills in the laboratory or in the field.

Among these factors, the most important are the stress level and the physical characteristics of rockfill particles and of the rockfill mass.

Deformation of rockfills due to a change in stresses causes two different effects: first, at the initial loading stages, there is an elastic compression of the individual rock particles. With increasing contact stresses, compressive strength may be reached, resulting in particle fracturing or rupture (Veiga Pinto, 1979).

With fracturing, the second effect becomes significant. This is the rearrangement of the granular structure, through sliding and rolling of individual particles, until a new equilibrium state is reached. Both effects, fracturing and rearrangement, may occur simultaneously and independently. The amount of fracturing and rearrangement depend on the degree of structural interlocking of rock particles. The interlocking is, in its turn, highly dependent on the relative density and stress level.

The stress state may therefore be considered the most important factor for correctly evaluating the behaviour of rockfills. Mineralogy and weathering degree are also important factors when analysing the mechanical properties of rockfills.

2 ALTERATION OF ROCKFILLS

Alteration of rocks occurs naturaly in time intervals of hundreds to thousands of years. In some cases, however, significant changes in rock properties may be noted in smaller time intervals, as low as a few months. (Fookes et al.; 1988, Maia et al., 2002). An impressive example reffers to the rapid alteration of a compact basalt rockfill in south Brazil, when exposed to atmospheric conditions. This fact resulted in significant changes of the construction especifications of Capivara Dam (Signer 1973, Frazão and Caruso 1983).

Alteration of rocks may be revealed by two basic mechanisms: disintegration and decomposition (Frazão, 1993). Simulation of these mechanisms through accelerated procedures in the laboratory is fundamental for studying and predicting the rate of weathering of rockfill materials.

Among such laboratory procedures, special atention has been given to the continuous lixiviation technique (Hypolito and Valarelli 1972; Farjallat 1972, Minette 1982, Maia et al. 2001). Details of a large size device, which was developed for continuous lixiviation of rockfills, has been reported by Maia et al. (2001). The continuous degradation through lixiviation causes loss of mineral contents and consequent modifications of the mechanical behaviour of rock particles. In basalt rockfills, lixiviation causes leaching of oxides, propagation of fissures, increase in deformability and reduction of strength (Maia et al., 2002 and 2003).

3 SHEAR STRENGTH OF ROCKFILLS

The shear strength parameters of coarse materials are usually obtained in direct shear or compression triaxial tests. Differences in results from these two tests are usually explained by several factors, such as stress conditions, stress paths, principal stress rotation, imposition of a failure plane, dilatancy restrictions, and stress nonuniformities (Becker et al., 1972; Nitchiporovitch and Rasskazov, 1976; Cea, 1998).

In laboratory testing of rockfills, attention must be given to the restriction on maximum particle dimension (d_{max}) to be allowed in a specific testing device. It is current practice to have a rockfill specimen with the smallest dimension (D) at least 4 to 6 times larger than d_{max}. These minimum values of D/d_{max} were recommended by Penman (1971) for well-graded and uniform rockfills, respectively.

When preparing a rockfill specimen, there must be similarities between the lab and the field materials. Apart from the obvious similarity in relative density, two important factors to be preserved are the shape of the grain size distribution curve and the shape of individual particles.

In well-graded materials, the number of particles contacts is higher and contact stresses are lower when compared to uniform materials. Uniform materials shall therefore experience a higher degree of particle fracturing.

4 ROCKFILL MATERIAL

For evaluating the relation between strength characteristics and alteration degree, a dark basalt rockfill was selected. This material was used as a riprap for protecting the upstream slope of Marimbondo Dam in Brazil (Figure 1). When the rockfill samples were being collected at the dam site (1998), the basalt had experienced about 25 years of natural alteration in the field, caused by cyclic fluctuations of ambient temperature and reservoir water level (Figure 2).

Samples of fresh basalt were also collected at a quarry, which was located about 1 km downstream from the dam. This quarry material was shown to be same intact basalt used during the dam construction (Maia, 2001).

The basalt is dark gray, dense and presents a homogeneous crystalline mass with fine to medium grains. Micro vesicles filled with secondary non-expansive minerals were observed in the basalt mass. The main minerals are plagioclase, pyroxene and olivine, with no traces of expansive minerals.

Rockfill particles of the weathered basalt present a marked alteration by decomposition and disintegration (Figure 3).

Figure 1 – Aerial view of Marimbondo dam and power plant.

Figure 2 – Upstream protection rockfill of Marimbondo dam.

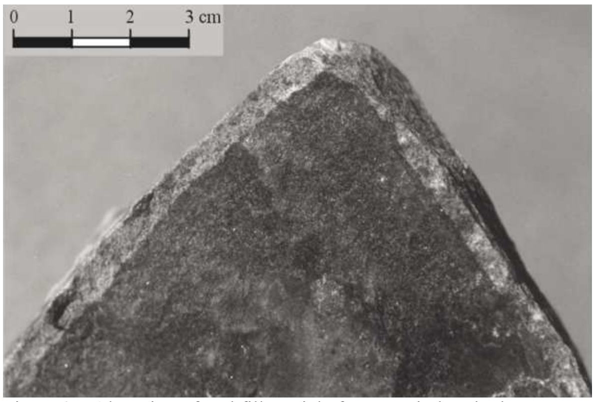

Figure 3 – Alteration of rockfill particle from Marimbondo dam.

5 EXPERIMENTAL PROGRAM

Large size direct shear and triaxial compression devices were used for testing rockfill materials. Both weathered and intact basalts were sent to Spain, for a comprehensive testing program carried out at CEDEX (Centro de Experimentación de Obras Públicas, in Madrid). Contrasting relative density Dr conditions of 30% and 90% were considered in the experimental program. Dry and submerged specimens were also tested in the direct shear device. The objective was to simulate the different construction procedures for loose and compacted rockfills dams and breakwaters.

The grain size distribution curves for the rockfill in the field and in the laboratory are shown in Figure 4. The lab curves were defined by modeling down the rockfill dimensions with a grain distribution parallel to the field material. The minimum value of D/d_{max} ratio was defined to be equal to 5.

In most direct shear tests, specimens were prepared cubic, with side dimensions of 1,00m and grain size curve A. Smaller specimens of 30 cm side dimensions (curve B) were also used for evaluating scale effects.

Triaxial compression tests were carried out under drained conditions, with 46cm high specimens of 23cm in diameter, also with grain distribution curve B.

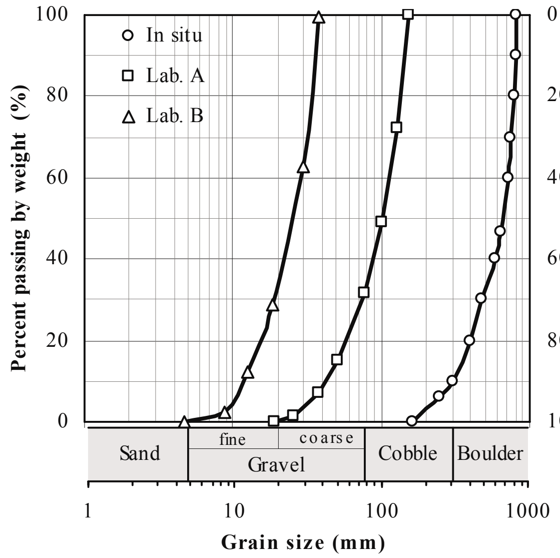

Figure 4 – Grain size distribution curves of rockfills.

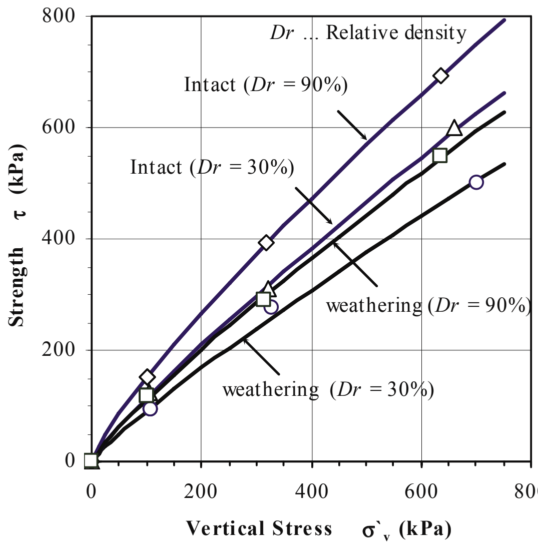

Figure 5 – Strength envelopes from direct shear tests on dry rockfill.

6 TEST RESULTS

Figure 5 presents the strength envelopes from direct shear tests on dense and loose specimens of weathered and intact rockfills.

Rockfill materials are noted to exhibit non-linear envelopes that may be expressed by a hyperbolic function, as suggested by Charles and Watts (1980). As a consequence, the values of friction angles are not constant, being highly dependent on the vertical effective stress.

Figure 6 presents results of tests executed in submerged rockfill in the smaller direct shear device. These results are already corrected for the effect of specimen dimensions, as reported by Maia (2001).

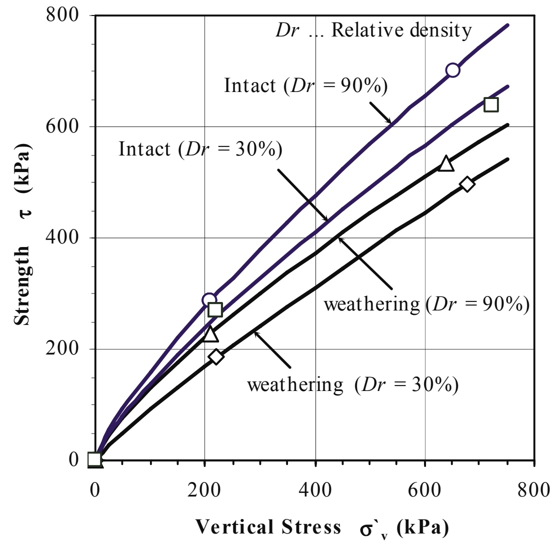

Figure 6 – Strength envelopes from direct shear on wet rockfill.

No significant differences may be noted between the shear strength envelopes from dry or wet rockfill, regardless of weathering or density conditions.

Figure 7 shows the failure envelopes from drained compression triaxial tests. These envelopes are noted to be not coincident to those shown in Figure 5 or 6. For a given range of effective stresses, the friction angles obtained from triaxial tests seem to be higher than those from direct shear, regardless of density or weathering characteristics of the rockfill.

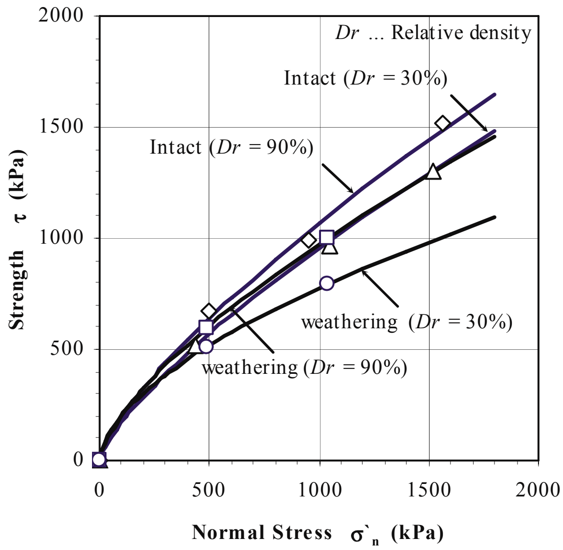

Figure 7 – Strength envelopes from triaxial shear tests.

7 DISCUSSION

The results presented in the previous section indicate that the shear strength increases with relative density and decreases with the weathering degree of the rockfill material.

A detailed study on the strength degradation of rockfill due to weathering was also carried out with continuously lixiviated specimens in the laboratory. The 25 years of natural weathering of the riprap material in the field were approximately reproduced by 430 hours of lixiviation of intact basalt in the laboratory. This correlation was proved to be specific for strength evaluation only. Another correlation was obtained for reproducing a different characteristic of the rockfill, such as stiffness. Details of the accelerated alteration procedure in the laboratory are reported elsewhere (Maia et al., 2001).

The laboratory results were useful for allowing an estimate of the strength envelope of the riprap material after more 50 years of field weathering (i.e., after a total of 75 years of natural degradation). This estimate is shown in Figure 8. The experimental results revealed that the rate of strength reduction due to weathering decays with time. Moreover, the strength envelope tends to a lower limit, which shall correspond to the completely weathered material. The methodology for extrapolating the experimental results on rockfill has been described in detail by Maia et al. (2003).

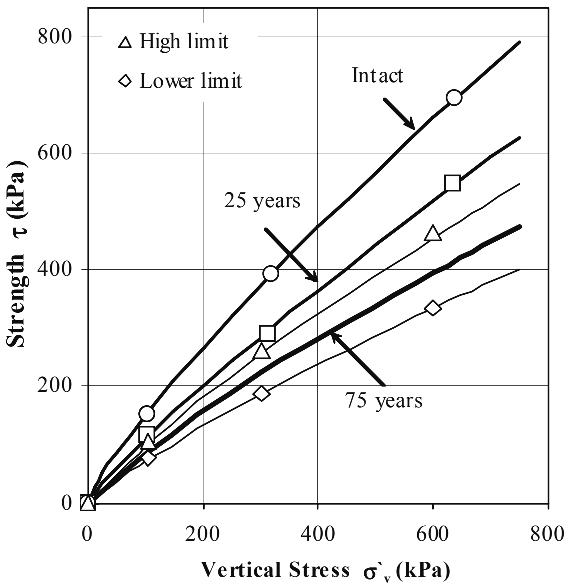

Figure 8 – Failure envelope estimates from weathering data.

8 CONCLUSIONS

This paper presents an evaluation of the shear strength of a basalt rockfill from the upstream riprap of Marimbondo Dam. Both natural and accelerated weathering conditions were considered for the rockfill in the experimental program. Direct shear and triaxial compression were carried out on large size specimens under different density and saturation conditions.

The results indicate that the strength envelope of rockfills are highly influenced by effective stress level, relative density and weathering degree of the rockfill.

A prediction of the strength envelope after 75 years of natural degradation of the rockfill is presented and discussed. With this prediction, it may be concluded that the rockfill is still adequate to function as an upstream protection riprap for at least more 50 years of dam operation.

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